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ANALYTICAL AND COMPUTER-AIDED MODELS OF INP-BASED MISFETS AND HETEROJUNCTION DEVICES

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L. J. Messick

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The superior properties of InP material, e.g., higher peak electron drift velocity, thermal conductivity, and breakdown field, to GaAs have made it an attractive alternative for high-performance applications in microwave and millimeter-wave regimes as well as high-speed digital circuits. Recently, a high-efficiency InP MISFET has demonstrated 4.5 watts output power with 4 dB gain and 46% power-added efficiency at 9.7 GHz by Messick et al. These impressive results clearly confirmed the promising superior performance of InP MISFETs.

The main concern in the applications of III-V MISFETs has been the reliability of output characteristics of the devices, which is mainly attributed to the variations of interfacial properties of the gate dielectric layer and the underlying semiconductor active layer. The task of modeling output characteristics of III-V compound-based MISFET devices has become more complex with the possible dominance of the interfacial properties in the devices' performance. Much more attention should be paid to the nonlinear modulation of the surface potential by the external gate voltage due to the presence of an excessive amount of interfacial states, since the accompanying carrier trapping, scattering, and recombination could have altered completely the charge control and transport mechanisms, and consequently the device output characteristics.

Because of these factors, we have developed analytical and computer-aided models for depletion-mode and accumulation-mode MISFETs based on a nonlinear charge control model derived from semi-empirical surface potential formulation, which can provide us not only an accurate description of the drain I-V characteristics, but also a comprehensive study of the influence of interfacial properties on the output performance of InP MISFETs. Key aspects of the physics of this device, which relate to charge control, carrier trapping, and field-dependent mobility, are modeled in this study.

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In order to further verify the calculated results and predict device performance in the submicron gate-length regime, we have developed a general finite-element two-dimensional semiconductor device simulation program, which is able to analyze and simulate various device structures including homo- and hetero-junctions III-V compound semiconductor-based devices with arbitrary geometries. Preliminary simulation results of a 1 μm AlGaAs/GaAs HEMT device are reported. It is planned to extend the two-dimensional model to submicron InP MISFETs.

Published in *InP Workshop Proceedings*, January 1989.

Analytical and Computer-Aided Models of InP-Based MISFETs and Heterojunction Devices*

A-J. Shey and W.H. Ku, UCSD and L. Messick, NOSC

Abstract

The superior properties of InP material, e.g., higher peak electron drift velocity, thermal conductivity, and breakdown field, to GaAs have made it an attractive alternative for high-performance applications in microwave and millimeter-wave regimes as well as high-speed digital circuits. Recently, a high-efficiency InP MISFET has demonstrated 4.5 watts output power with 4 dB gain and 46% power-added efficiency at 9.7 GHz by Messick et al.[1] These impressive results clearly confirmed the promising superior performance of InP MISFETs.

The main concern in the applications of III-V MISFETs has been the reliability of output characteristics of the devices, which is mainly attributed to the variations of interfacial properties of the gate dielectric layer and the underlying semiconductor active layer. The task of modeling output characteristics of III-V compound-based MISFET devices has become more complex with the possible dominance of the interfacial properties in the devices' performance. Much more attention should be paid to the nonlinear modulation of the surface potential by the external gate voltage due to the presence of an excessive amount of interfacial states, since the accompanying carrier trapping, scattering, and recombination could have altered completely the charge control and transport mechanisms, and consequently the device output characteristics.

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References

[1] L. Messick et al., "High-Power High-Efficiency Stable Indium Phosphide MISFETs," *Proc. of the IEDM*, p. 767-770, 1986.

*This work was supported by NOSC under Contract N66001-85-C-0422.

Analytical and Computer-Aided Models of InP-Based MISFETs* and Heterojunction Devices**

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+ Dept. of Electrical and Computer Engineering, University of California, San Diego

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* Research supported by NOSC under Contract No. N66001-85-C-0422.

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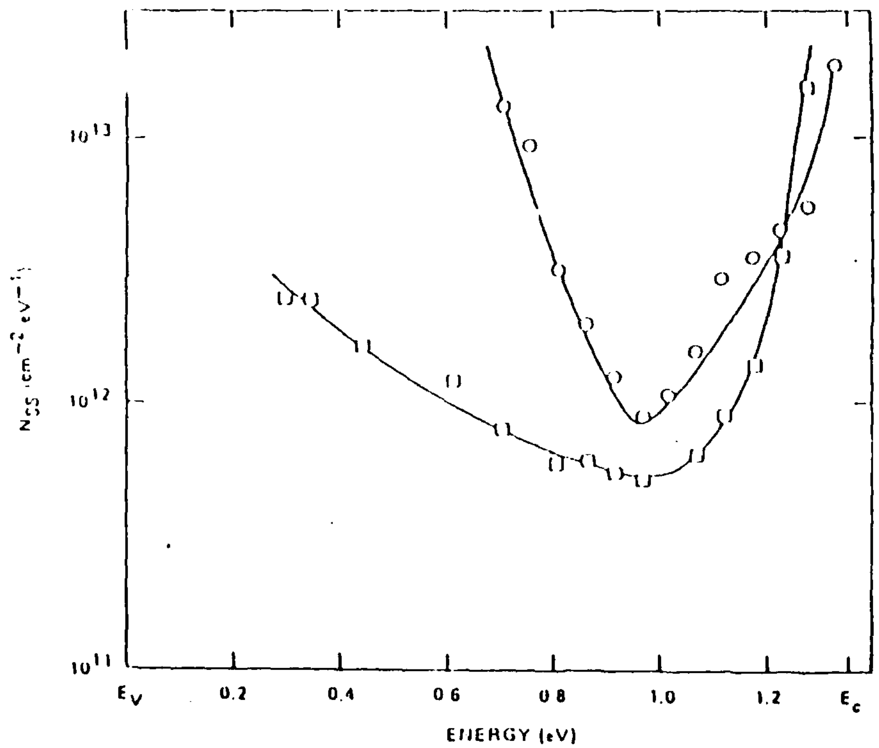
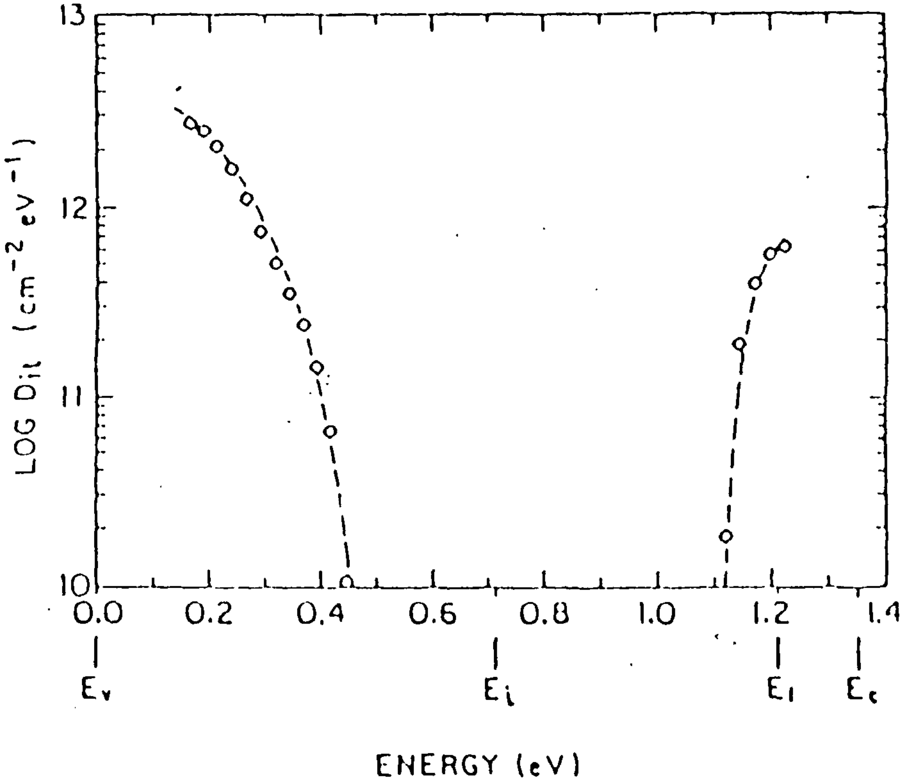
- Introduction
- 1–D MISFET Model*
- 2–D HEMT Model**

Typical Distribution of Interface State Density within Energy Band Gap Measured by C – V or Optical Methods



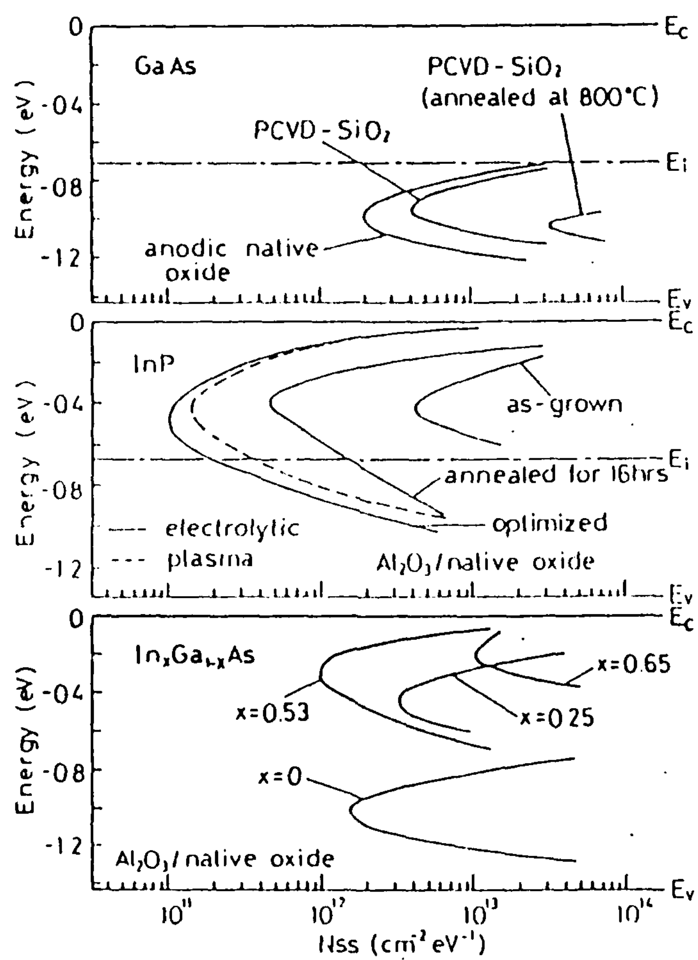
From H. H. Wieder, Surface Science 133 (1983) 390.



From P. D. Gardner *et al. IEEE Electron. Dev. Lett.*,

EDL-8 (1987) 45.

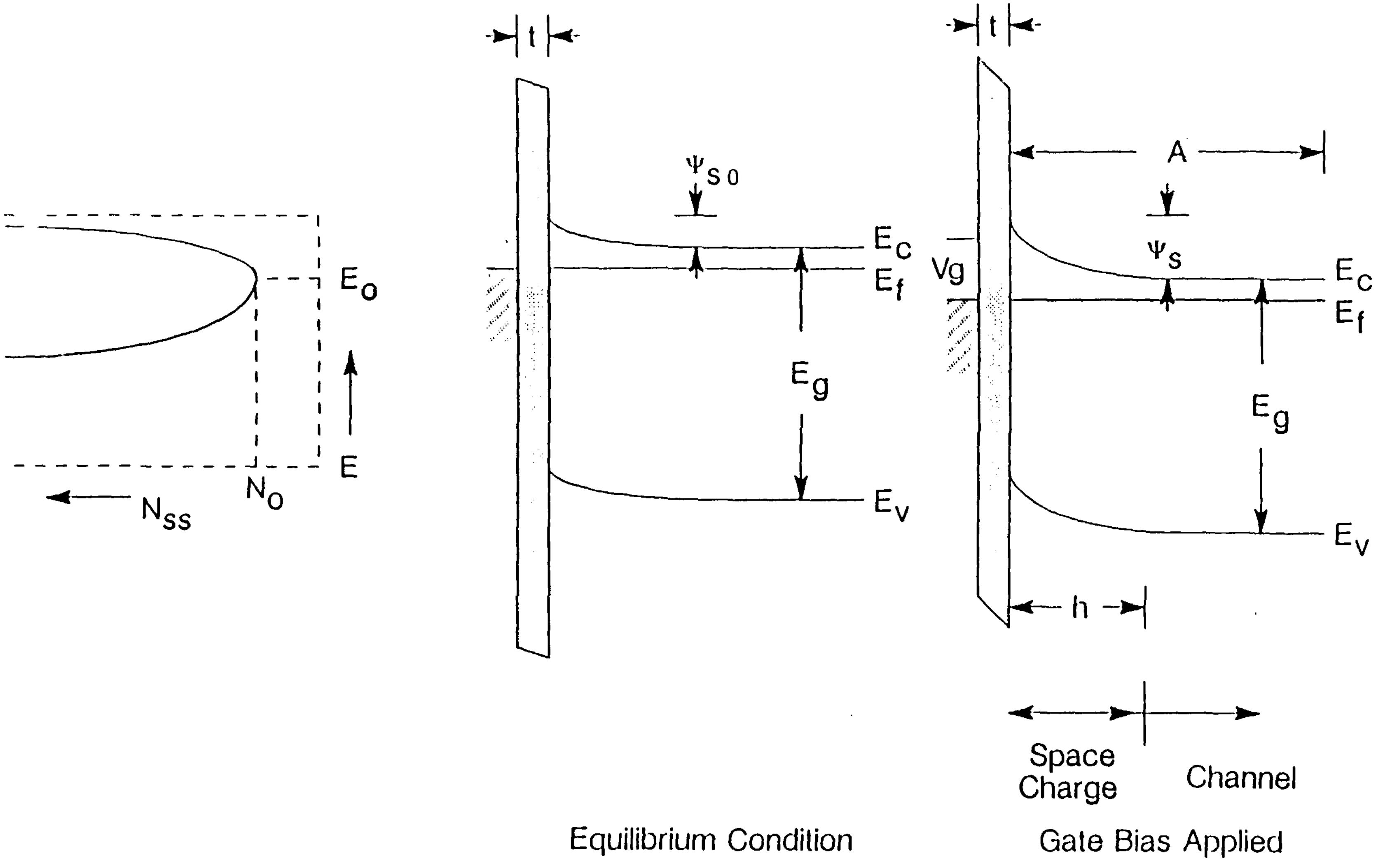
Typical Distribution of Interface State Density within Energy Band Gap Measured by C -- V or Optical Methods



Measured N_{ss} distribution of the I-S interfaces, using C–V and PCTS methods. Note that no peaks in the N_{ss} distribution are observed. While minimum N_{ss} and U-shape curvature depends on processing conditions, the location of N_{ss} minimum remains constant for each semiconductor.

From H. Hasegawa *et al. J. Vac. Sci. Technol.*, B, Vol. 4, (1986) 1130.

Energy band diagram of an n-type InP MIS structure



Charge control model

By Gauss law

Electrical field at the interface of insulator and semiconductor

$$E - E_o = -\frac{1}{\epsilon_d}\left[(Q_s - Q_{so}) + (Q_{ss} - Q_{sso})\right]$$

Q_s : *space charge*

Q_{ss} : *interface state charge*

subscript o : *equilibrium state value*

$$V_g - V(x) = -\frac{t}{\epsilon_d}\left[(Q_s - Q_{so}) + (Q_{ss} - Q_{sso})\right] + (\psi_{so} - \psi_s)$$

t : *insulator thickness*

ϵ_d : *insulator permittivity*

$V(x)$: *channel potential*

ψ_s : *surface potential*

Distribution of interface states within energy band gap

Existing model (uniform interface states distribution model)* :

$$N_{ss} = N_o \quad : \quad constant$$

$$\Delta Q_{ss} = q N_o \left(\psi_s - \psi_{so} \right)$$

Hasegawa's DIGS model :

$$N_{ss} = \begin{cases} N_o \exp\left[\left(\dfrac{E - E_o}{E_{oa}} \right)^{n_a} \right] & E \geq E_o \\ N_o \exp\left[\left(\dfrac{E_o - E}{E_{ob}} \right)^{n_b} \right] & E \leq E_o \end{cases}$$

$$\Delta Q_{ss} = -q \left(\int N_{ss} f(E)\, dE \Big|_{\psi_s} - \int N_{ss} f(E)\, dE \Big|_{\psi_{so}} \right)$$

$f(E)$: *the occupation function*

Variable interface states distribution model :

Simplified Hasegawa's model with $n_a = n_b = 1.0$

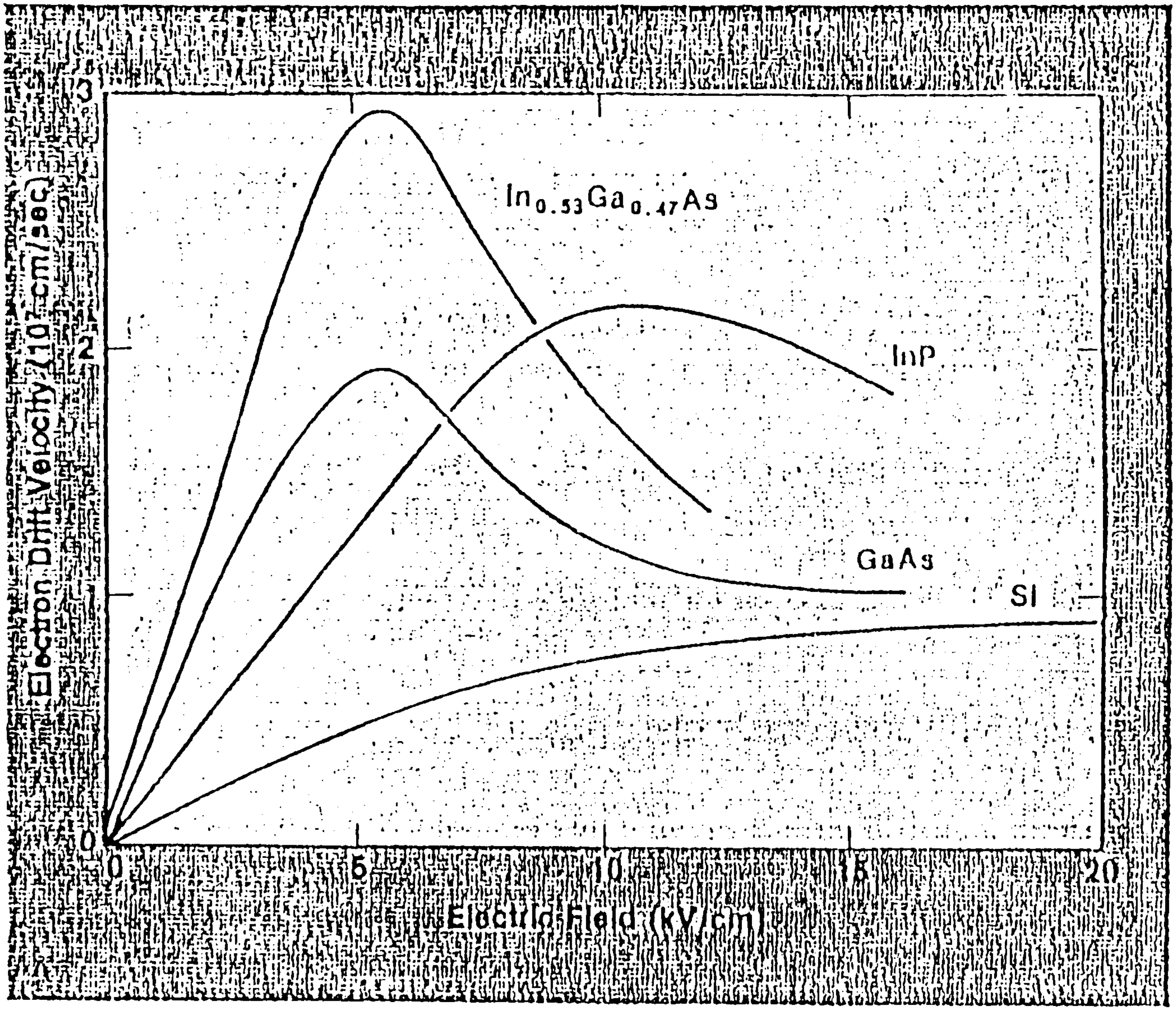
* R. Pucel *et al.*, *Advances in Electronics and electron Devices*, 38 (1975) 195.
D. Lile, *Solid-State Electron.*, 21 (1978) 1199.
P. Hill, *IEEE Trans. Electron Devices* ED-32 (1985) 2249.

The empirical velocity versus electrical field model*

$$\upsilon = \begin{cases} \dfrac{\left(\mu + \dfrac{\upsilon_{sat}}{E_C} \right) E}{1 + \dfrac{E}{E_C}} & E \leq E_S \\[2ex] \upsilon_{sat} & E \geq E_S \end{cases}$$

where $\upsilon_{sat} = \mu E_S$

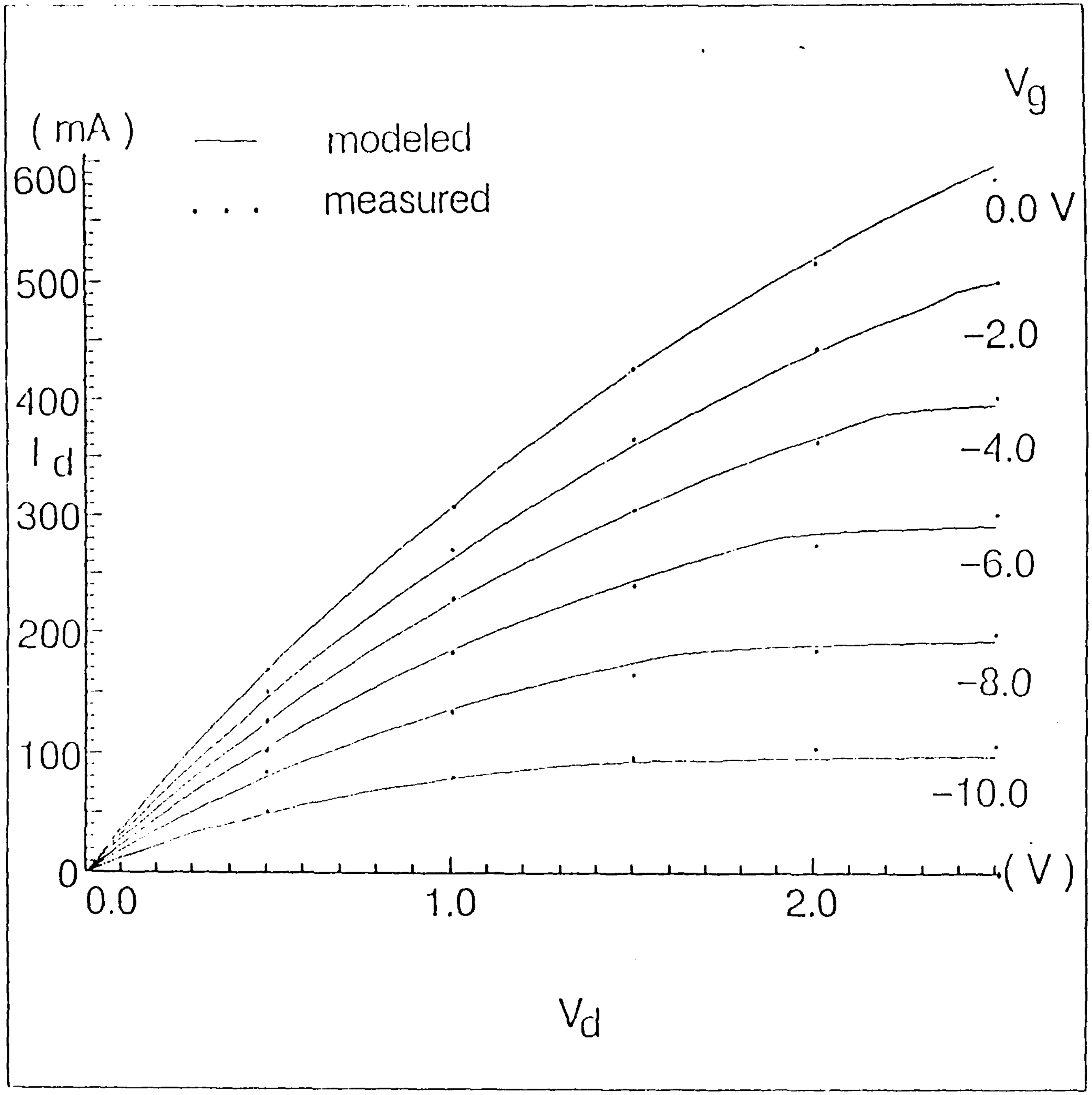
* W. Curtice, *IEEE Trans. Electron Devices*, ED-29 (1982) 1942.



Electric Drift Velocity vs. Electric Field (300 K)

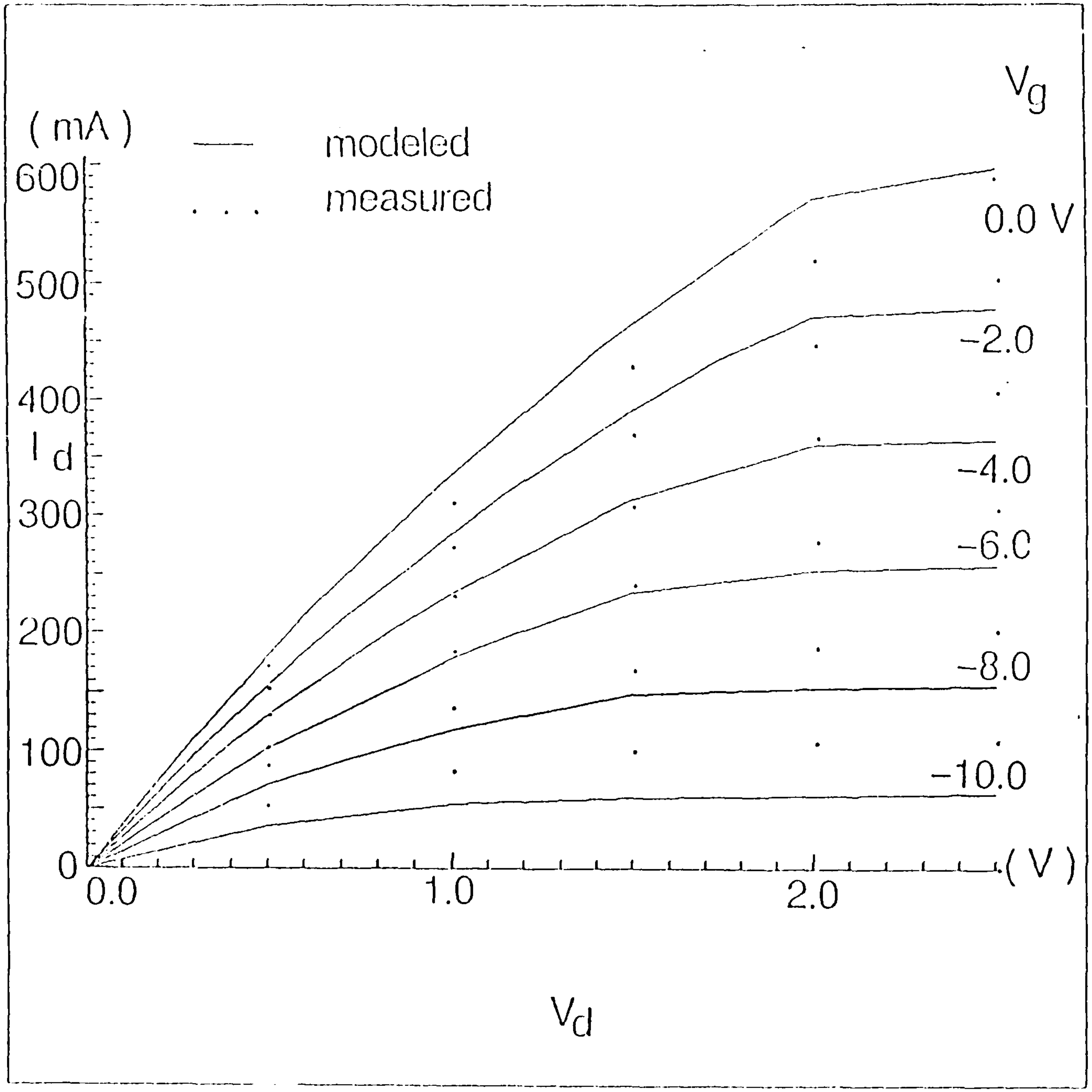
From H. Morkoc *et al.* *Solid State Technology*, 31 (1988), 83.

Modeled Drain I – V Characteristics by Variable Interface State Distribution Model



Measured data from L. Messick *et al.*, IEDM (1986) 767.

Modeled Drain I – V Characteristics by Uniform Interface State Distribution Model



Measured data from L. Messick *et al.*, IEDM (1986) 767.

Device parameters used in MISFET models
for the best fit to the measured data

	variable density model	uniform density model	unit	
L	1.4	1.4	μm	*
Z	1000	1000	μm	*
A	0.2	0.2	μm	*
t	1000	1000	Å	*
μ	2000	2000	cm^2 / Vs	*
E_C	2.0×10^4	2.0×10^4	V / cm	*
E_S	1.15×10^4	1.15×10^4	V / cm	*
υ_{sat}	2.38×10^7	2.38×10^7	cm / s	*
ϵ_d	3.9	3.9	ϵ_o	*
ϵ_s	12.4	12.4	ϵ_o	*
N_D	1.4×10^{17}	1.4×10^{17}	cm^{-3}	*
Eg	1.34	1.34	V	*
ψ_{so}	0.42	0.98	V	
N_o	1.2×10^{11}	0	$cm^{-2} eV^{-1}$	
E_{oa}	0.11		V	
E_o	$Ec - 0.34$		V	
Rs	0.6	0.6	Ω	*
Rd	0.6	0.6	Ω	*

Two-dimensional Simulation of III–V Compound Semiconductor Devices

Objectives :

- Use two–dimensional simulation to assist in the analysis and modeling of short–channel effects.
- Include momentum balance and energy balance equations to take hot carrier effects into account.

Features :

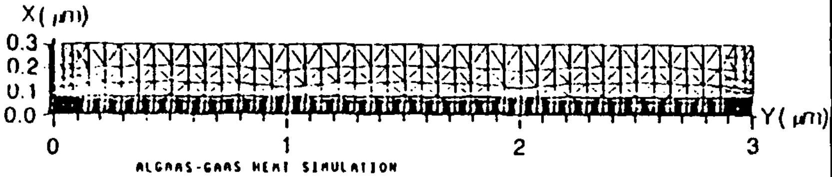
- New finite–element discretization method*
- Fermi–Dirac statistics
- Velocity overshoot effect

* W. Ku *et al. IEEE Trans. CAD,* to appear in May 1989

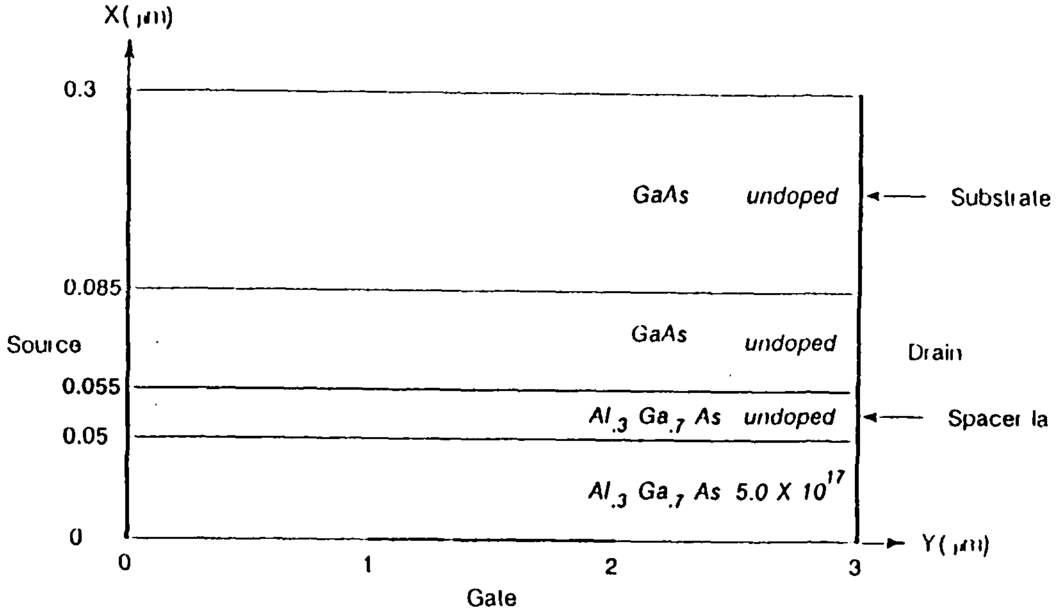
Simulation Mesh

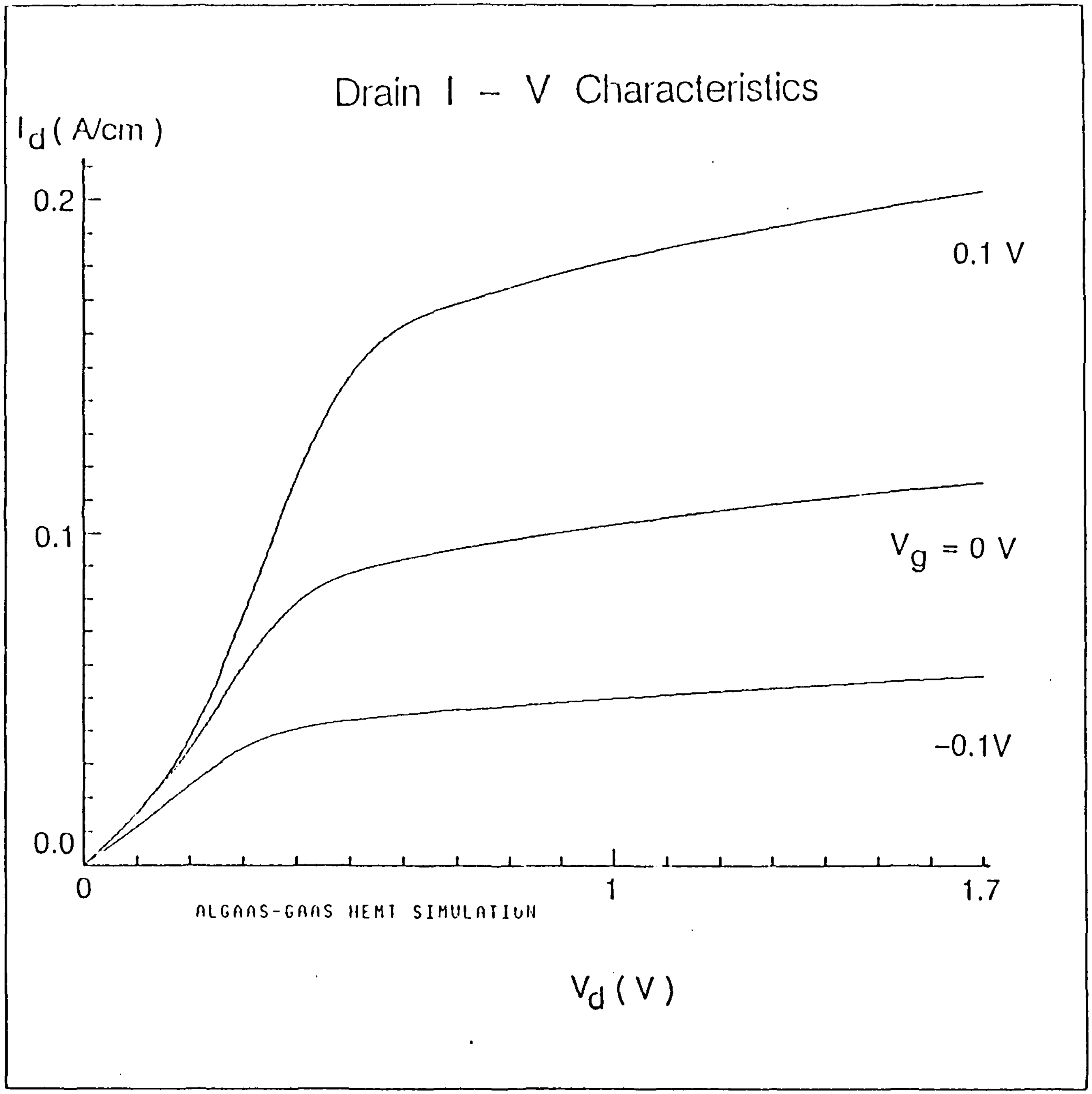
# of points = 1273

# of elements = 2380

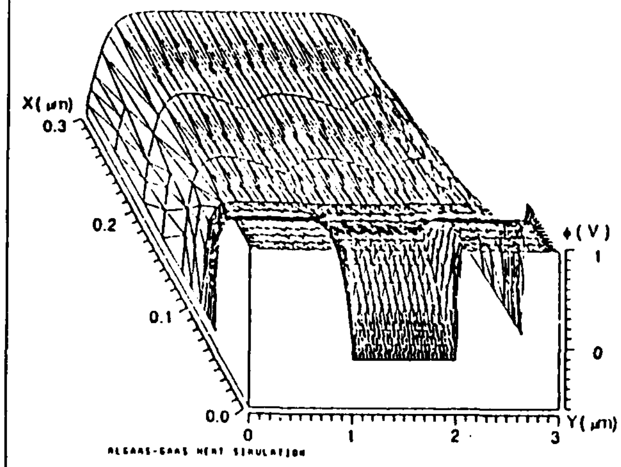


AlGaAs / GaAs HEMT Device Structure Used for Simulation

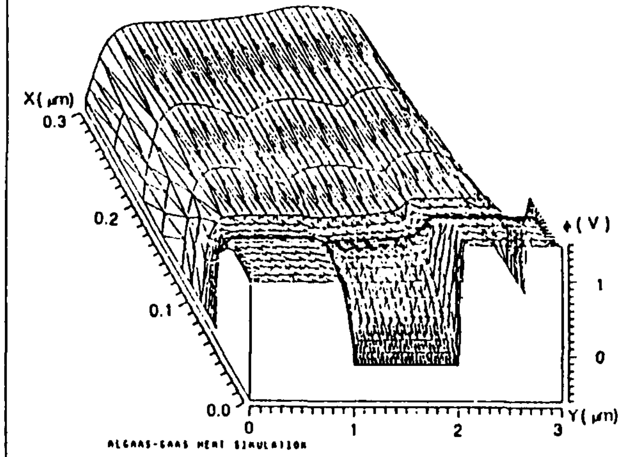



Drain I – V Characteristics
Id (A/cm)
0.2
0.1
0.0
0
1
1.7
0.1 V
Vg = 0 V
-0.1V
ALGAAS-GAAS HEMT SIMULATION
Vd (V)

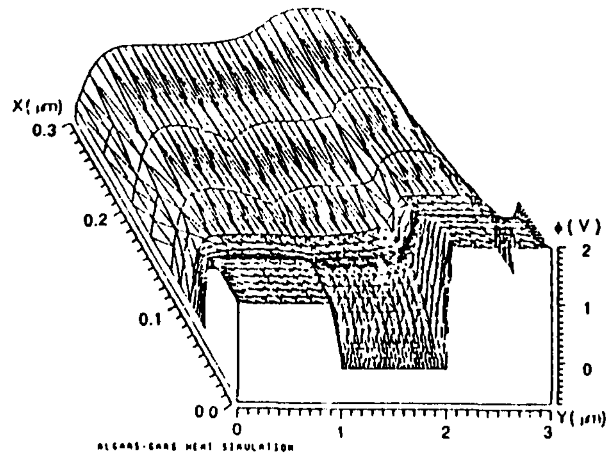
Potential Distribution (V_g = 0 V , V_d = 0 V)



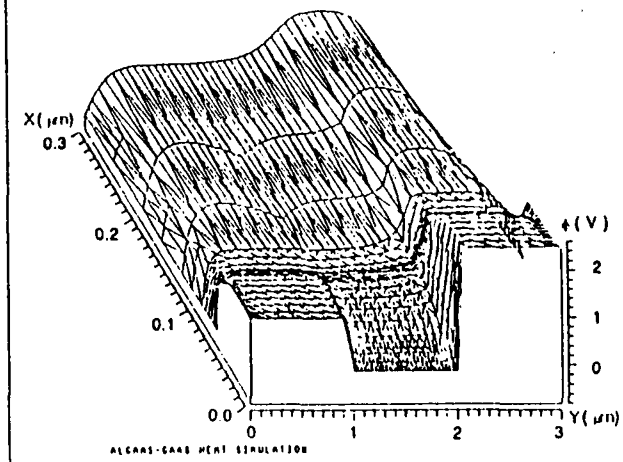
Potential Distribution (V_g = 0 V , V_d = 0.5 V)



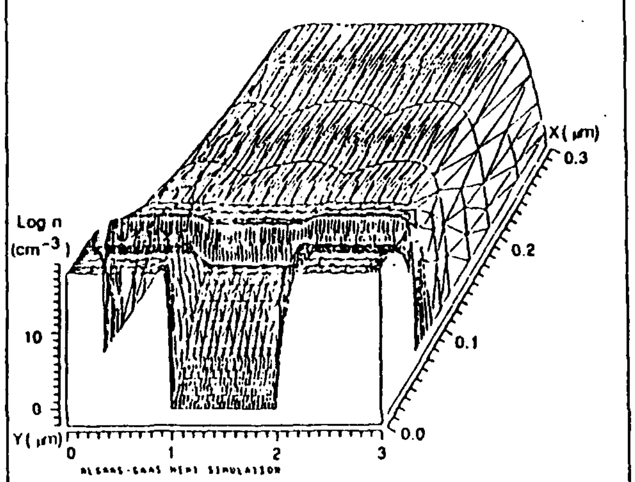
Potential Distribution (V_g = 0 V , V_d = 1.0 V)



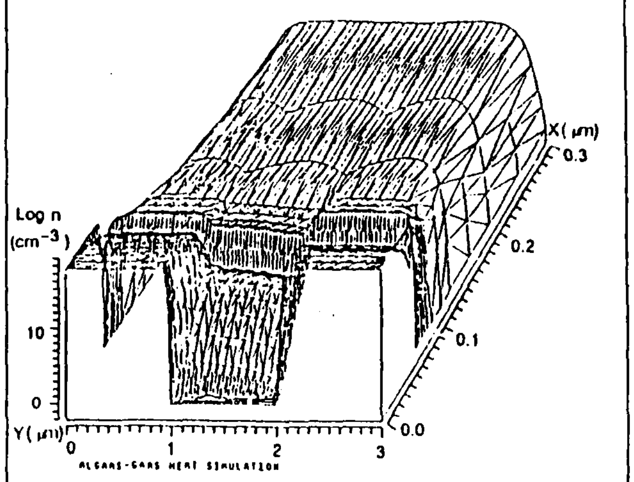
Potential Distribution (V_g = 0 V , V_d = 1.5 V)



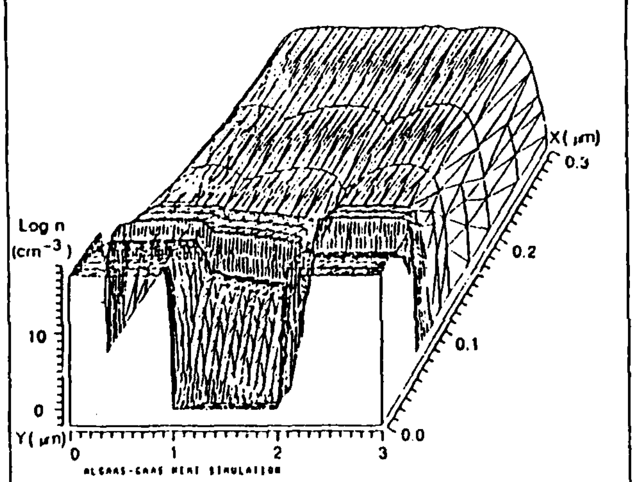
Electron Distribution ($V_g = 0$ V , $V_d = 0$ V)



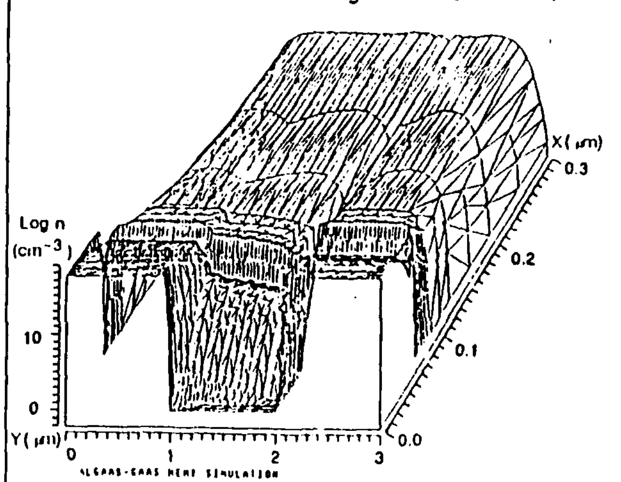
Electron Distribution ($V_g = 0$ V , $V_d = 0.5$ V)



Electron Distribution ($V_g = 0$ V , $V_d = 1.0$ V)



Electron Distribution ($V_g = 0$ V , $V_d = 1.5$ V)



Summary

- The inclusion of interface states distribution profile into drain I – V characteristics model leading to a more accurate description of output performance of MISFETs
- Successful implementation of a two–dimensional model for HEMT devices based on a new finite–element discretization method
- Plan to apply the two–dimensional numerical model to the modeling of submicron gate length MISFETs and HEMTs